

LP 400-22, A VERY LOW-MASS AND HIGH-VELOCITY WHITE DWARF

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ABSTRACT

We report the identification of LP 400-22 (WD 2234+222) as a very low-mass and high-velocity white dwarf. The ultraviolet *GALEX* and optical photometric colors and a spectral line analysis of LP 400-22 show this star to have an effective temperature of $11\,080 \pm 140$ K and a surface gravity of $\log g = 6.32 \pm 0.08$. Therefore, this is a helium core white dwarf with a mass of $0.17 M_{\odot}$. The tangential velocity of this white dwarf is 414 ± 43 km s⁻¹, making it one of the fastest moving white dwarfs known. We discuss probable evolutionary scenarios for this remarkable object.

Subject headings: stars: atmospheres — white dwarfs — stars: individual (LP 400-22)

1. INTRODUCTION

The vast majority of white dwarfs evolve from normal main-sequence stars following normal evolutionary processes. However, ultramassive ($> 1.1 M_{\odot}$) and infamassive ($< 0.40 M_{\odot}$) white dwarfs require special evolutionary paths. The formation of low-mass helium white dwarfs ($M_{WD} \lesssim 0.4 M_{\odot}$) has been shown to be the result of close binary evolution (Iben & Tutukov 1986, and references therein). Indeed, the Galaxy is not old enough for these objects to have formed through single star evolution. The general evolutionary scenario for the formation of low-mass helium white dwarfs is that the companion stripped the white dwarf of its envelope before completing its red giant evolution (Kippenhahn et al. 1967).

Recently, several very low mass white dwarfs ($M_{WD} \lesssim 0.2 M_{\odot}$) have been discovered as companions to pulsars (van Kerkwijk et al. 2005). The orbital periods vary from a few hours to several years. The masses of some of these white dwarfs may be determined from the Shapiro delay of radio pulses provided that the system is nearly edge on (Löhmer et al. 2005). For example, Jacoby et al. (2003) deduced a mass of $0.20 M_{\odot}$ for the companion of PSR J1909–3744, and obtained a spectrum which confirmed, at least qualitatively, the presence of a low mass DA white dwarf. In addition, the masses of the companions to PSR J1012+5307 and PSR J1911–5958 were determined spectroscopically to be $0.16 M_{\odot}$ (van Kerkwijk et al. 1996; Callanan et al. 1998) and $0.18 M_{\odot}$ (Bassa et al. 2006), respectively. Finally, several low-mass white dwarf candidates were found in the Sloan Digital Sky Survey (Kleinman et al. 2004). Liebert et al. (2004) analyzed the brightest star in the

sample, SDSS J123410.37–022802.9 and showed that it has a mass of $\sim 0.18 M_{\odot}$ and that it does not have an obvious neutron star companion.

In this paper, we report the identification of a high velocity white dwarf with a very low mass, LP 400-22 (WD2234+222², NLTT 54331). Our photometric and spectroscopic observations are presented in §2.1 and 2.2 respectively. We derive the stellar parameters in §3 and discuss our results in §4.

2. OBSERVATIONS

LP 400-22 was spectroscopically identified as a white dwarf as part of a survey of common-proper motion binaries with suspected white dwarf components (Oswalt et al. 1993). We obtained additional high-resolution optical spectra (Silvestri 2002) as well as new optical photometry (Smith 1997) as part of the same project. More recently, LP 400-22 was observed during the *Galaxy Evolution Explorer* (*GALEX*) all-sky survey.

2.1. Photometry

The *BVRI* photometry for LP 400-21/22 were obtained with the 2.1m telescope at KPNO on 1995 July 5 UT. A Tek1K CCD (with $24\mu\text{m}$ pixels) operating at the Cassegrain focus was used, providing $0''.305$ per pixel and a $5\frac{1}{2}$ field of view. The data for LP 400-21/22 were obtained under photometric conditions. Standard stars for this program were chosen from Landolt (1992).

We obtained ultraviolet (UV) photometry from *GALEX* All-Sky Survey³. *GALEX* provides photometry in two bands, FUV and NUV, which are based on the AB system (Morrissey et al. 2005; Oke & Gunn 1983). The bandwidth of FUV is 1344 to 1786 Å with an effective wavelength of 1528 Å. The bandwidth of NUV is 1771 to 2831 Å with an effective wavelength of 2271 Å.

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² Online at <http://www.astronomy.villanova.edu/WDCatalog/index.html>

³ Available from <http://galex.stsci.edu/GR1/>

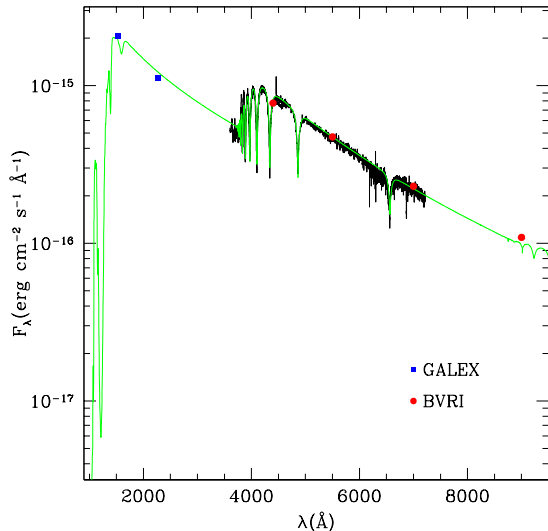


FIG. 1.— The energy distribution of LP 400-22 combining all available data compared to our H-rich model spectrum at $T_{\text{eff}} = 11\,000$ K and $\log g = 6.50$ (see §3).

TABLE 1
PHOTOMETRY

Band	LP 400-22	LP 400-21
FUV ^a	18.38 ± 0.09 mag	...
	18.18 ± 0.08 mag	...
NUV ^a	18.19 ± 0.05 mag	...
	18.14 ± 0.04 mag	...
B	17.338 ± 0.025 mag	18.742 ± 0.025 mag
V	17.219 ± 0.021 mag	17.177 ± 0.021 mag
R	17.202 ± 0.023 mag	15.933 ± 0.023 mag
I	17.210 ± 0.024 mag	14.340 ± 0.023 mag

^aThe mean of these values are used in this paper.

Table 1 presents the optical and ultraviolet photometry and Figure 1 shows the energy distribution compared to a synthetic spectrum.

2.2. Spectroscopy

We obtained a low-resolution spectrum of LP 400-22 using the R-C spectrograph attached to the 4 m telescope at Kitt Peak National Observatory (KPNO) on 1988 October 6. The BL250 grating (158 lines/mm) was used to obtain a spectral range of 3500 to 6200 Å with a dispersion of 5.52 Å per pixel and a resolution of 14 Å.

LP 400-22 was re-observed using the Dual Imaging Spectrograph (DIS) attached to the 3.5 m telescope at the Apache Point Observatory (APO) on 2001 July 10 and October 14. The 1200 lines/mm grating was used to obtain a spectral range of 3800 to 4600 Å with a dispersion of 1.6 Å per pixel, and the 830.8 lines/mm grating was used to obtain a spectral range of 6180 to 7210 Å with a dispersion of 1.3 Å per pixel. A 1''5 slit was used to obtain a spectral resolution of ~ 2 Å in the blue and ~ 2.6 Å in the red.

3. DETERMINING THE PARAMETERS

In our analysis of LP 400-22, we used a grid of computed pure hydrogen LTE plane parallel models (see

Kawka & Vennes (2006) and references therein for details). The grid of models extend from $T_{\text{eff}} = 7000$ to 16 000 K (in steps of 1000 K), from 18 000 to 32 000 K (in steps of 2000 K) and from 36 000 to 84 000 K (in steps of 4000 K) at $\log g = 6.0$ to 9.5 (in steps of 0.25 dex). All our $\log g$ values are in cgs. We also prepared corresponding grids of synthetic spectra, one of which includes the effect of Ly α satellites (Allard & Koester 1992), and the other excludes that effect.

3.1. Photometry

Using our spectral grid, we have calculated synthetic optical (*BVRI*) and ultraviolet (*FUV/NUV*) colors. Figure 2 shows the observed photometric colors ($V - FUV$ versus $FUV - NUV$ and $B - V$ versus $V - R$) of LP 400-22 compared to synthetic white dwarf and main-sequence colors. We used Kurucz synthetic spectra (Kurucz 1993) to calculate our main-sequence colors.

In the UV-optical diagram ($V - FUV/FUV - NUV$) of Figure 2 we show two sets of WD synthetic colors. The grid shown in black includes the effect of Ly α satellites (Allard & Koester 1992) as compared to the grid in green which excludes them. A comparison of the two grids shows the significant effect that the Ly α satellites have on the UV colors at $T_{\text{eff}} < 13\,000$ K. Comparing the UV-optical photometry of LP 400-22 to the white dwarf grid, a low surface gravity $\log g \sim 6$ and an effective temperature of $\sim 11\,000$ K is implied. The optical diagram ($B - V/V - R$) in Figure 2 confirms the white dwarf temperature of 11 000 K and the low surface gravity.

However, when comparing the photometry to main-sequence colors, a A3V spectral type is implied in the optical and a B8V spectral type in the ultraviolet. Therefore, the data are incompatible with main-sequence colors. Optical and UV colors are useful to distinguish white dwarfs from main-sequence stars.

3.2. Spectroscopy

The Balmer lines of LP 400-22 were analyzed in all three available spectra using a χ^2 minimization technique. The quoted uncertainties are statistical only (1σ). The Balmer lines (H β to H9) in the KPNO spectrum were fitted with model spectra which were smoothed to the instrumental resolution of 14 Å, to obtain $T_{\text{eff}} = 11\,000 \pm 350$ K and $\log g = 6.48 \pm 0.27$. For the two high-resolution APO spectra we fitted H α and H γ to H9 with model spectra, to obtain $T_{\text{eff}} = 11\,060 \pm 180$ K and $11\,160 \pm 250$ K, and $\log g = 6.46 \pm 0.13$ and 6.22 ± 0.10 . The synthetic spectra used in the analysis of the APO spectra were smoothed with a gaussian profile to the instrumental resolution of 2 Å. Note that the discrepancy in the surface gravities from the 2 APO spectra are most likely the result of uncertainties in the flux calibration around the higher Balmer lines. The Balmer line fit of the KPNO spectrum is shown in Figure 3. These measurements clearly confirm that LP 400-22 is a white dwarf with a low surface gravity. The calculated weighted average of the temperature and surface gravity is $T_{\text{eff}} = 11\,080 \pm 140$ K and $\log g = 6.32 \pm 0.08$.

We used the evolutionary tracks for helium-core white dwarfs of Althaus et al. (2001) and Serenelli et al. (2001) to determine a mass of $0.17 \pm 0.01 M_{\odot}$ and a cooling age of $5 \pm 1 \times 10^8$ years. Note that the cooling age of the white dwarf is sensitive to the mass of the hydrogen

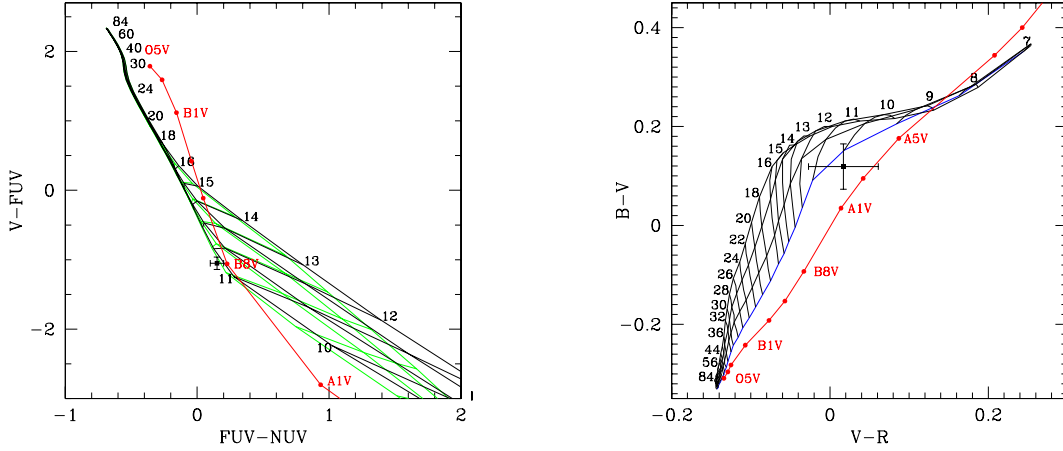


FIG. 2.— *GALEX* V-FUV versus FUV-NUV (left) and optical B-V versus V-R (right) diagrams showing the position of LP 400-22 compared to the DA white dwarf sequence and the main-sequence (in red). The effective temperatures are indicated in units of 1000 K and the $\log g = 6.0, 7.0, 8.0$ and 9.0 (from bottom to top). In the optical diagram $\log g = 6.0$ is indicated by the blue line. In the UV-optical diagram, the grid shown in black includes the Ly α satellite and the grid in green does not.

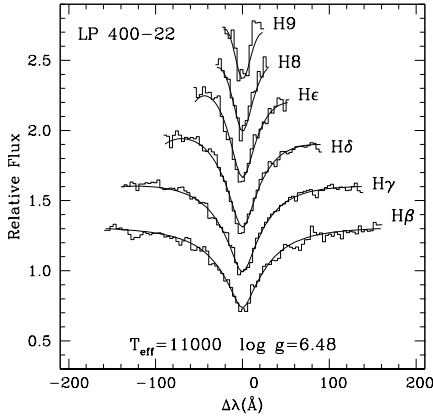


FIG. 3.— Spectral fit of the Balmer lines (H β to H9) of the KPNO spectrum of LP 400-22.

envelope left before entering the final cooling track (see Althaus et al. 2001, and references therein). Residual H-burning in a thick H-envelope causes the white dwarf to cool slower as compared to a white dwarf with a thin H-envelope.

The temperature of 11080 K places LP 400-22 near the blue edge of the ZZ Ceti instability strip (Gianninas et al. 2005). Given the lack of time coverage in our data, we cannot state whether the star is variable or not. Time-series photometry is required to explore variability and place constraints on the blue edge of the instability strip at the low-mass range.

4. DISCUSSION

LP 400-22 was listed in the New Luyten Two-Tenths (NLTT) catalog (Luyten 1979) to have a common proper motion companion (LP 400-21) $338''$ away. Recently, Salim & Gould (2003) have revised the coordinates and proper motions of most stars in the NLTT catalog by cross-correlating the catalog with the Two Micron All Sky Survey (2MASS) and the USNO-A catalogs. However LP 400-22 was not detected in 2MASS, and there-

fore they relisted Luyten's measurement of the proper motion. They listed the proper motion of LP 400-22 to be $\mu_\alpha = 0''.1950 \pm 0''.0200 \text{ yr}^{-1}$ and $\mu_\delta = 0''.0563 \pm 0''.0200 \text{ yr}^{-1}$. For LP 400-21 they measured a proper motion of $\mu_\alpha = 0''.2158 \pm 0''.0055 \text{ yr}^{-1}$ and $\mu_\delta = 0''.0283 \pm 0''.0055 \text{ yr}^{-1}$. These proper motion measurements agree within 2σ and on this basis the two stars appear to be a common proper motion binary. However, similar measurements were reported by Lepine & Shara (2005), i.e., $\mu_\alpha = 0''.198 \text{ yr}^{-1}$ and $\mu_\delta = 0''.053 \text{ yr}^{-1}$ for LP 400-22, and $\mu_\alpha = 0''.228 \text{ yr}^{-1}$ $\mu_\delta = 0''.020 \text{ yr}^{-1}$ for LP 400-21. The quoted uncertainties in the Lepine & Shara (2005) measurements are $\sim 0''.007 \text{ yr}^{-1}$ and, therefore, the diverging proper motions of the two stars appears to exclude a physical association. Another way to check whether the stars are a physical binary is to determine the distance of each star.

To estimate the distance, we calculated an absolute magnitude of $M_V = 9.1 \pm 0.2 \text{ mag}$ for LP 400-22 and a distance modulus $(V - M_V) = 8.2 \text{ mag}$. This places the white dwarf at a distance of $430 \pm 45 \text{ pc}$. Note that the Galactic extinction for this object is low and its effect was not included. Silvestri et al. (2005) classified LP 400-21 a dM4.5e, and using the $M_V/V - I$ relation from Reid & Gizis (1997) we estimate the absolute magnitude of the red dwarf as 12.7 mag. The apparent V magnitude for LP 400-21 is $V = 17.177 \pm 0.021 \text{ mag}$, and, therefore, the red dwarf is at a distance of $\sim 80 \text{ pc}$. Reid & Gizis (1997) note a scatter of values about the relation with $\sigma = 0.46$. Even if we consider LP 400-21 at the extrema of this dispersion, it would place it at a distance of only $\sim 100 \text{ pc}$. The large distance discrepancy makes LP 400-22/21 a coincidental pair rather than a wide binary as has been thought based on their proper motion alone.

The large distance and high-proper motion of LP 400-22 imply a large tangential velocity of $414 \pm 43 \text{ km s}^{-1}$. Only a few white dwarfs are known to have $v_{\text{tan}} > 350 \text{ km s}^{-1}$, with most of these having halo space velocities (Bergeron et al. 2005). In order to obtain the U, V, W space velocity components for LP 400-22, we measured the radial velocity of the white dwarf using

TABLE 2
LP 400-22 PARAMETERS

Parameter	Measurement	Reference
Effective Temperature	$11\,080 \pm 140$ K	1
Surface Gravity	6.32 ± 0.08	1
Mass	$0.17 \pm 0.01 M_{\odot}$	1
M_V	9.1 ± 0.2 mag	1
Distance	430 ± 45 pc	1
Proper Motion	$\mu = 0''.203 \text{ yr}^{-1}, 0''.205 \text{ yr}^{-1}$ $\theta = 73.9^{\circ}, 75.0^{\circ}$	2,3 2,3
Kinematics	$U = -388 \pm 43 \text{ km s}^{-1}$	1
	$V = -81 \pm 22 \text{ km s}^{-1}$	1
	$W = -83 \pm 22 \text{ km s}^{-1}$	1

REFERENCES. — (1) This work; (2) Luyten (1979); Salim & Gould (2003); (3) Lepine & Shara (2005)

H α in the APO high-dispersion spectra to obtain a heliocentric value of $-50 \pm 20 \text{ km s}^{-1}$, which is different than the velocity measured for the red dwarf (7.3 km s^{-1}) by Silvestri et al. (2002). We calculated U, V, W for LP 400-22 using Johnson & Soderblom (1987) to obtain $U = -388 \pm 43$, $V = -81 \pm 22$, $W = -83 \pm 22 \text{ km s}^{-1}$. These velocity components do not agree with either disk or halo populations (Chiba & Beers 2000) and suggest a different origin for its peculiar motion. The Galactic orbit for LP 400-22 should be calculated.

Most white dwarfs with $M < 0.2 M_{\odot}$ are companions to pulsars. We searched for radio sources in the vicinity of LP 400-22 using *VizieR*⁴, and the nearest was that of the galaxy KUG2234+223 $\sim 7.5'$ away. Therefore, if LP 400-22 is a companion to a neutron star, then it is probably a dead pulsar. Another possibility is that LP 400-22 has a very cool companion, which should be detectable as infrared excess. However, LP 400-22 was not detected by 2MASS. The two high-dispersion velocity

measurements agree within error bars. However, a series of radial velocity measurements should be obtained to establish whether or not LP 400-22 is in a close binary system.

Yet another possibility for the origin of LP 400-22 is that it may have once been in a close double-degenerate binary, where the companion has gone through a supernova event that disrupted the binary losing the remnant of the donor star with a high-velocity and a low mass (Hansen 2003).

5. SUMMARY

We have demonstrated that LP 400-22 is a high-velocity white dwarf with a very low mass ($M = 0.17 M_{\odot}$) and a temperature of 11 080 K. Table 2 summarizes the properties of LP 400-22. Since white dwarfs with masses below $0.4 M_{\odot}$ must have been formed in close binary systems, radial velocity measurements and infrared photometry are required to determine whether LP 400-22 has a close companion. On the other hand, a lack of radial velocity variations would indicate that LP 400-22 lost its close massive companion following a type Ia supernova event.

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⁴ <http://vizier.u-strasbg.fr/viz-bin/VizieR>

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